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A critical review on microwave, fluidised-bed and convective air-drying of low rank coals: The water diffusivity on coals.

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Abstract. A critical review on drying of low rank coal drying using conventional air-drying, fluidised bed drying and microwave drying methods. The parameters of different drying methods that affected the water effective diffusivity values were identified and critically discussed in details including hot air temperatures, flow rates, particle sizes, particle weights, and microwave powers. The microwave and fluidised bed drying methods are more effective in drying of low rank coal compared to the conventional hot air drying method. This is because the microwave drying method can heat up the internal part of the coal, thus leads to a higher drying rate and effective diffusivity values whereas the fluidised bed causes an uniform distribution of heating medium to heat up the low rank coal and the fluidisation resulted in a better mixing performance and a higher heat and mass transfer compared to the conventional hot air drying. Moreover, Midilli-Kucuk model was the best and most commonly used drying model for drying of the low rank coal. In the fluidised bed drying, the Midilli-Kucuk was the best-fitted drying model to dry the low rank coal whereas Wang & Singh model was the best drying model in the fixed-bed drying for the coarse particle of low rank coal. The microwave drying kinetics can be modeled using either the Page Model or Midilli-Kucuk model. Further to this, it was found that few parameters that significantly affected the effective diffusivity of the low rank coal are increasing temperature and flow rates of the convective air-drying meanwhile increasing the particle size and particle weight results in a decrease in effective diffusivity value for the fluidized-bed drying.

1. Introduction

Coal was formed from decaying animal corpse and plants where their remains sank into swampy waters, making layers and layers, which is subjected to heat and pressure for millions of years. Coals are differentiated into four types which are lignite, subbituminous, bituminous, and anthracite. Low rank coal such as lignite is estimated to have 45% of the world's coal reserves [1].

Gross calorific value (also known as heating value) of a coal is the total heat released when combusted. Higher gross calorific value of coal means that more heat energy is produced during combustion which is then converted into electricity in a power plant. It is reported that low rank coal have a gross calorific value (GCV) of 10-16 MJ/kg while high rank coal have a gross calorific value of 18-25.5 MJ/kg [2]. Figure 1(a) and 1(b) show two subbituminous coals from Merit Pila in Kapit. The specification of this Merit Coal has a total moisture 20% wet basis. Volatile matter, fixed carbon content and ash content are 39%, 36% and 10% respectively. Gross calorific value (GCV) of this coal is 22.19 MJ/kg, which is considered as a medium-high rank coal.

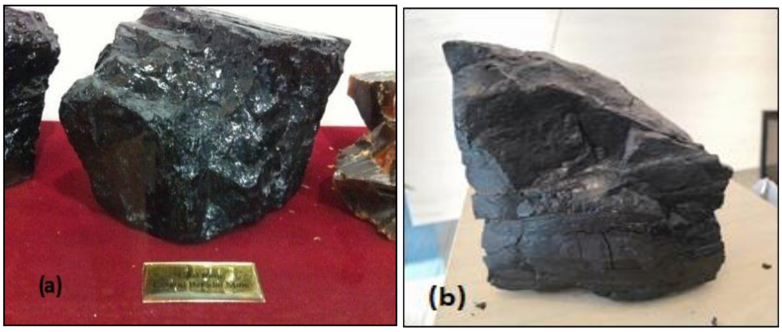

Figure 1(a) and 1(b). Subbituminous low rank coal at the Merit Pila

Moisture found in coal can be affected by internal and external factors. A number of oxygen functional groups leads to a high moisture content and hydrophilicity in low rank coal [3]. Internal factor is affected by the inherent moisture where water is entrapped in the microporous structure [3]. On the other hand, external factors such as geographical age, location and humidity of atmosphere can affect the moisture content of coal. Moisture content of low rank coal such as lignite ranges from 30% to 70% wet basis [4]. A report shows that the inherent moisture of the coal needs to be removed first as it reduces energy efficiency of combustion in power plant by 20-25% [4].

Until now, most studies focus on the drying methods of low rank coal to increase the efficiency of a power plant. This study provides a critical review on parameters that affected the water effective diffusivity. The objective is to evaluate the effective diffusivity of low rank drying dried using the conventional hot air drying, fluidised bed drying and microwave drying methods. In addition, this paper covers assessment of selected mathematical models used for modelling of drying kinetics and Fick's 2nd law used to determine water diffusivity values. The three main research questions are

- Will microwave drying and fluidised bed drying method be more efficient than conventional hot air drying by improving the effective diffusivity of low rank coal?
- What empirical model can be used in low rank coal drying by using three different drying methods?
- How will the parameters of drying methods affect the effective diffusivity of low rank coal?

Figure 2 shows the flow of this literature. First, coals are differentiated into two categories which are steam coal and coking coal. Steam coal was used to generate electricity by burning it. In addition, the drying in low rank steam coal was discussed using a conventional hot air drying, fluidised bed drying and microwave drying. The effective diffusivity is estimated using the Fick's second law and it was found out that there are three empirical models, which can get the best fit for each drying methods. Finally, the parameters of each drying methods were discussed on how do different parameters affect the effective diffusivity.

Drying of low rank coal is vital because the removal of moisture is essential to effectively use low rank coal for power generation [5]. However, removal of moisture can have potential danger such as spontaneous combustion during processing [5]. A critical review of three different drying methods used in drying low rank coals are shown in Figure 2.

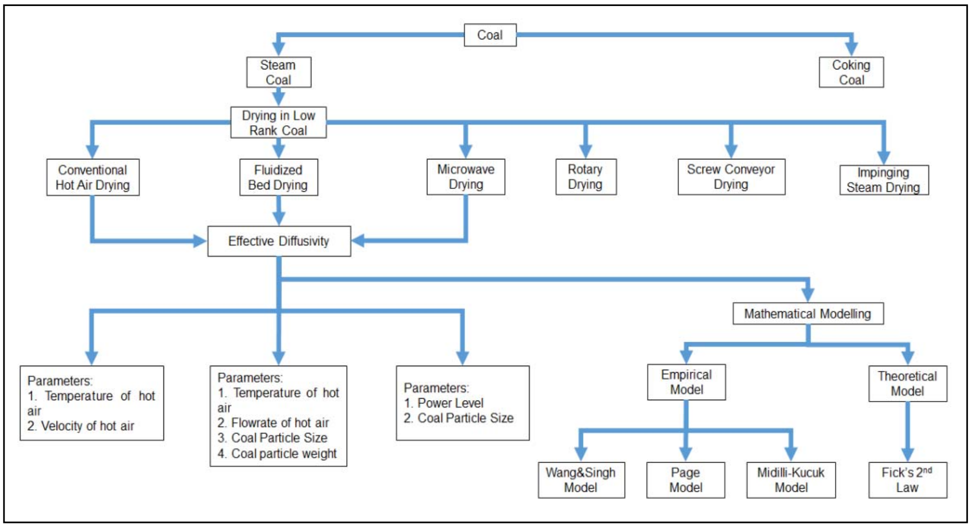

Figure 2. Diffusivity in drying of low rank coal

2.1 Conventional Hot Air Drying
Conventional hot air drying is commonly used in drying processes. Conventional hot air drying is a direct heating method because hot air is used as the medium to dry coal. Figure 3 shows that hot dry air is supplied to diffuse out surface moisture of a coal, as a result creating a pressure gradient between the inner part and surface of the coal [6]. In this process, the temperature gradient enhanced the ability of hot dry air to dry the coal [6]. Hence, this causes inherent moisture to diffuse from the inside to the surface of the coal [7].

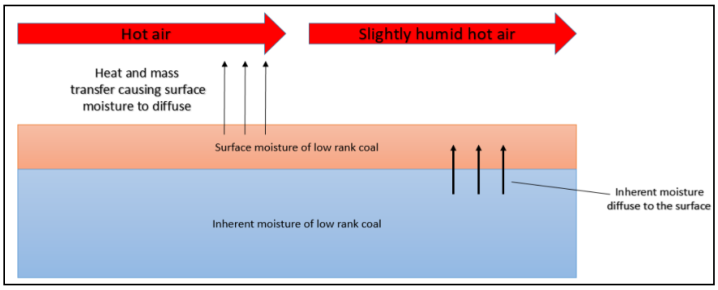

Figure 3. Schematic diagram of indirect heating using conventional hot air drying

2.2 Fluidised Bed Drying
Fluidised bed method decreased the initial moisture content of brown coal from 50 to 15wt% (wet basis) [8]. Fluidised bed dryers are widely used for industrial low rank coal drying because of their compact structure, good mixing performance, and high heat and mass transfer rates [9]. The drying mediums used in a fluidised bed are hot air or combustion gases or superheated steam [3]. It is a direct heating method where the drying medium is supplied from the bottom of the bed of particulate solids causing heat and mass transfer to occur between solid and gas. The fluidised bed uniformly distributed across the bed. If the hot air flow rate is greater than the settling flow rate of the particles and lower than the flow rate of pneumatic conveying, fluidisation occurs. The mixture of solid and gas behaves like a liquid. An object with higher density will sink and a lower density object will float, thus fluidised bed exhibits fluid behaviour. The intense mixing between solid and gas will result in a uniform temperature distribution of the solids resulting in good mixing performance and high heat and mass transfer rate.

2.3 Microwave Drying

Microwave drying method decreases the coal moisture content from 52% to 10% [3]. Microwave drying is a form of indirect heating because it uses electromagnetic waves to generate heat in a non-conducting material without any direct heating source. It was found out that as the electromagnetic waves oscillate induces the rotation of dipoles of water causes ions to vibrate, spin, and collide back and forth against each other to realign to the electromagnetic waves resulting in the possible breaking of hydrogen bonds [10] shown in Figure 4(a). This creates thermal energy in the form of dielectric loss or molecular friction in the internal water molecule of the coal which result in internal water to diffuse out of the coal from the internal part and dries the coal causing it to have polarisation effect increased the effective diffusivity value of the coal. Moreover, the microwave heating is more unique compared to conventional hot air drying and fluidised bed because the drying samples are heated from the inside to the outside instead of outside heating to the inside of the drying sample. **Figure 4(b)** shows how microwave drying is heated (red) and **Figure 4(c)** shows how conventional hot air drying and fluidised bed are heated(red) .

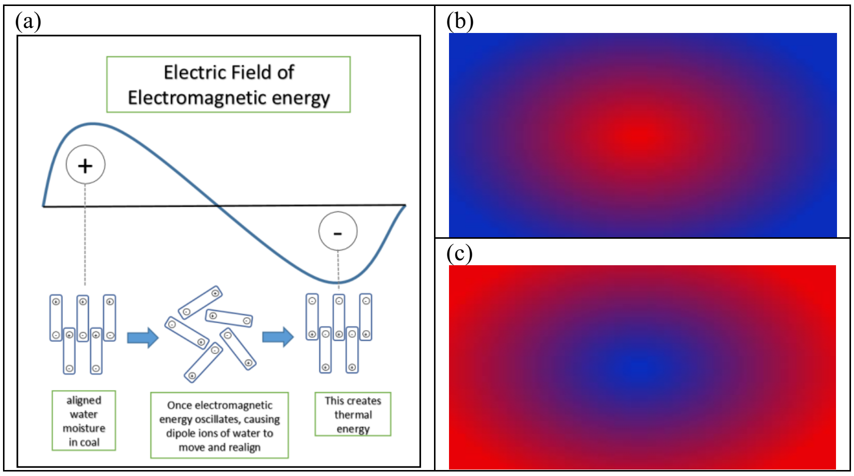

Figure 4(a) Movement of water molecules with oscillation of electromagnetic energy **(b) & (c)** Difference of microwave drying compared to conventional hot air drying and fluidised drying.

3.0 Mathematical modelling

Based on Table 1, it was found out that the Midilli-Kucuk was the best and most used drying model to dry low rank coal using the conventional hot air drying, fluidised bed drying, and microwave drying. The Midilli-Kucuk model can be expressed by the following equation:

$$MR = aexp(-kt^n) + bt$$

Further to this, fluidised bed drying in thin layer drying for low rank coal were conducted in Shengli lignite with a range of R_2 from 0.998 – 0.999, $\varkappa^2$ from 0.00216 – 0.0316 and RMSE from 0.00669 – 0.0217 which was proven to be the best fit using the Midilli-Kucuk model [11]. This model is also suitable for microwave drying process for drying low rank coal. According to Zhu et al. [12], Ximeng lignite was best fitted using the Midilli-Kucuk model with a range of R_2 from 0.9982 – 0.9996, $\varkappa^2$ from 0.0001 – 0.0002 and RMSE from 0.0076 – 0.0127. Other than this model, the Wang & Singh model was the best drying model for a fixed bed drying according to Pusat et al. [13].

The Wang & Singh model is best fitted drying model for drying low rank coal such as Turkish lignite in a fixed bed drying shown in Table 2. The Wang & Singh model can be expressed by the following equation:

$$MR = 1 + at + bt^2 \tag{1}$$

Fixed bed drying is similar to fluidised bed drying. Thus, some similar literature study on modelling can be compared. Tahmasebi et al. [14], Stokie et al. [15], Zhao et al. [11] were conducted using fluidised bed drying and the results were most fitted in Midillli-Kucuk model shown in Table 2. In addition, from fixed bed drying had two best drying model using the Midilli-Kucuk model and Wang & Singh model. According to Tahmasebi et al. [16], the fixed bed drying was conducted using thin layer particle of Chinese lignite. In contrast, Pusat et al. [3] uses coarse particle Turkish lignite to undergo fixed bed drying. It can be concluded that for thin layer drying using fixed bed drying, the Midilli-Kucuk model is the most suitable drying empirical model whereas the Wang&Singh model is highly recommended when drying coarse particle of low rank coal using fixed bed drying. Besides, the Page model was a suitable drying model conducted by Tahmasebi et al. [14].

Page model can be expressed by the following equation:

$$MR = exp(-kt^n) \tag{2}$$

Referring to Table 1, the Ximeng lignite and Highvale subbituminous coal best fitted model was the Midilli-Kucuk model [12] [17]. However, the Shenhua No.6 lignite best fitted model was the Page model when dried using the microwave drying by Tahmasebi et al. [14]. The difference in the result can be explained by the following reasons:

- Coals used are different. Subbituminous coals have lower moisture content than lignite. Hence result may vary.
- Parameters used in the Ximeng lignite and Shenhua No.6 lignite are different. For example, Ximeng lignite was conducted using microwave power of 300 W, 500 W and 700 W with 5 g mass of coal and 154-600 µm coal particle size. Conversely, Shenhua No.6 lignite uses microwave power of 380 W, 540 W and 700 W and different coal particle size of 150-500 µm, 500-1000 µm and 1000-1600 µm. Hence different results.

In conclusion, the Midilli-Kucuk drying model can be used for all three drying methods introduced in this literature which are conventional hot air drying, fluidised bed drying and microwave drying method. Moreover, for coarse particle low rank coal, it is recommended to use the Wang & Singh drying model in fixed bed drying. For microwave drying, either the Page model or the Midilli-Kucuk model are suitable to be used as the drying model.

Table 2. Best drying model for different drying methods in low rank coal

Coal	Drying Methods	Best Drying Model	Reference
Shengli lignite	Fluidised Bed Drying	Midilli-Kucuk Model	[11]
Shenhua No.6 Lignite	Nitrogen Fluidised Bed Drying Superheated Steam Fluidised Bed Drying		[14]
Victorian Brown Coal	Superheated Steam Fluidised Bed Drying Air Fluidised Bed Drying		[15]
Chinese Lignite	Fixed Bed Drying		[16]
Ximeng Lignite	Microwave Drying		[12]
Highvale Sub-bituminous Coal	Microwave Drying		[17]
Chinese Lignite	Conventional Hot air Drying		[18]
Turkish Lignite	Fixed Bed Drying	Wang&Singh Model	[13]
Shenhua No.6 lignite	Microwave Drying	Page Model	[14]

4.0 Effects of different drying methods

4.1 Conventional Hot Air Drying. A study on a conventional hot air drying was found out to have an increase in effective diffusivity value above 80%. 40 g of Chinese Hebei Lignite was used to evaluate how temperature and flow rate of hot air affect the effective diffusivity value. Three experiments were conducted by using flow rate of hot air of 0.6 m/s, 1.4 m/s, and 2.0 m/s by Fu and Chen [18]. Each experiment was conducted with increasing temperature from 100^{0}C to 160^{0}C shown in the Table 3. When the temperature increased from 100 to 160^{0}C with 0.6 m/s hot air flow rate, the effective diffusivity value increased 122% from 5.098 x10$_{-9}$ to 1.126 x10$_{-8}$ m$_2$/s in the first falling rate and 114% increase in the second falling rate. The effective diffusivity value increased at elevated temperature due to temperature is the main driving force. With an increase in hot air temperature, the enhancement of heat and mass transfer resulting in a faster migration of inherent moisture to the surface [18]. Further to this, higher hot air flow rate had a higher increase in effective diffusivity value compared to lower hot air flow rate. For example, at 160^{0}C, the effective diffusivity are 1.126 x10$_{-8}$ m$_2$/s, 1.329 x10$_{-8}$ m$_2$/s and 1.481 x10$_{-8}$ m$_2$/s at hot air flow rate of 0.6 m/s, 1.4 m/s and 2.0 m/s respectively. This is due to higher hot air flow rate have higher mass and heat transfer with the surface of the coal, as a result creating a pressure gradient between the surface and inner part of the coal [6]. The pressure gradient leads inherent moisture to diffuse to the surface and heated up by the hot air, thus dry coal obtained.

Table 3. Effective diffusivity of conventional hot air drying [18]

Samples and Constants	Drying Method & Parameters	Effective diffusivity
Chinese Hebei Lignite	Conventional Hot Air Drying	i)first falling rate ; ii)2nd falling rate (m2/s)
	100°C	i)5.098 x10$_{-9}$; ii)7.003 x10$_{-9}$
	110°C	i)5.610 x10$_{-9}$; ii)8.063 x10$_{-9}$
	120°C	i) 6.928 x10$_{-9}$; ii)9.638 x10$_{-9}$
(10mm,40g, & 0.6m/s)	130°C	i)8.238 x10$_{-9}$; ii)1.106 x10$_{-8}$
	140°C	i)8.533 x10$_{-9}$; ii)1.227 x10$_{-8}$
	150°C	i) 9.660 x10$_{-9}$; ii)1.248 x10$_{-8}$
	160°C	i)1.126 x10$_{-8}$; ii)1.496 x10$_{-8}$
	100°C	i)4.343 x10$_{-9}$; ii)9.060 x10$_{-9}$
	110°C	i)7.585 x10$_{-9}$; ii)1.096 x10$_{-8}$
	120°C	i)8.888 x10$_{-9}$; ii)1.238 x10$_{-8}$
(10mm,40g & 1.4m/s)	130°C	i)9.320 x10$_{-9}$; ii)1.430 x10$_{-8}$
	140°C	i)1.045 x10$_{-8}$; ii)1.613 x10$_{-8}$
	150°C	i)1.248 x10$_{-8}$; ii)1.684 x10$_{-8}$
	160°C	i)1.329 x10$_{-8}$; ii)1.724 x10$_{-8}$
	100°C	i)7.303 x10$_{-9}$; ii)9.920 x10$_{-9}$
	110°C	i)8.793 x10$_{-9}$; ii)1.207 x10$_{-8}$
	120°C	i)9.953 x10$_{-9}$; ii)1.355 x10$_{-8}$
(10mm,40g & 2.0m/s)	130°C	i)1.106 x10$_{-8}$; ii)1.430 x10$_{-8}$
	140°C	i)1.187 x10$_{-8}$; ii)1.552 x10$_{-8}$
	150°C	i)1.349 x10$_{-8}$; ii)1.745 x10$_{-8}$
	160°C	i)1.481 x10$_{-8}$; ii)1.907 x10$_{-8}$

4.2 Fluidised Bed Drying. The effective diffusivity value of the Shenghua No.6 coal dried using different fluidised bed drying parameters was investigated. The hot air temperature used to dry the sample ranged from 100^{0}C to 250^{0}C. Figure 5 was plotted with a x-axis of temperature of hot air to compare different parameters dried using method associated with fluidised beds drying. The types of associated methods are superheated steam fluidised bed (SSFB), fixed bed drying (FBD) and nitrogen fluidised bed (NDB). The effective diffusivity value dropped 43% was reported by Tahmasebi et al. [14] as shown in Figure5a when evaluating the particle size 0.075 and 0.05 mm at 200^{0}C constant gas temperature dried using the superheated steam fluidised-bed drying method with. The increased in particle size has led to decrease in effective diffusivity value could be due to the huge particle size has smaller specific surface area. Then, the resulted in a lower mass and heat transfer rate. Internal heat and mass transfer are better for smaller particles, and the smaller particles have larger heat and mass transfer surface area [13]. In addition, the effect of sample weight affected the diffusivity values.

The fixed-bed drying method shown in Figure 5b effective diffusivity value dropped 75% when sample weight increased from 1 to 10 g [16]. The hot air temperature used in this experiment was fixed at 150^{o}C. Also, drying sample weight of 5 g and 10 g results in a decrease of effective diffusivity value from 1.91 x 10^{-10} to 0.93 x 10^{-10} m^2/s, a 51.31% decreased in effective diffusivity value. This is because smaller coal sample weight contains less inherent moisture in weight basis [16]. The increase in sample weight leads to a lower mass transfer rate of inherent moisture from the internal coal to the surface, therefore reduces effective diffusivity value. Further to this, gas flow rate used in fluidised bed had a significant effect on the effective diffusivity value.

Nitrogen fluidised bed was used at different gas flow rate of 100 and 300 L/h at a constant temperature of gas of 200^{o}C shown as Figure 5c [14]. The result was an increase in 54% of effective diffusivity value from 2.8 x 10^{-10} to 4.3 x 10^{-10} m^2/s. This is because when the fluidised bed drying process is under external heat transfer control (convective boundary condition) [14]. Hence this leads to higher inherent moisture to diffuse out of the coal, decreasing the moisture content of the coal [15].

Tahmasebi et al. [14] used nitrogen fluidised bed, superheated steam fluidised bed and fixed bed drying to evaluate on the gas temperature of fluidised bed shown as Figure 5 di, dii and diii respectively. Three different lines shown in Figure 5 shows that an increased in gas temperature leads to an increased in effective diffusivity value. The effective diffusivity value increases at elevated temperature is because temperature is the main driving force that leads to higher heat transfer, resulting in a higher drying rate and effective diffusivity [16].

Moreover, the 3.0 g of Shenhua No.6 effective diffusivity value is shown Figure 5di. It was found that there is a 113% increase of effective diffusivity value from 4.0 x 10^{-10} to 8.5 x 10-10 m^2/s at drying temperature ranged from 150 to 250^{o}C. In Figure 5dii, 2.0 g of sample coal dried using the same temperature ranged. The results show a 90% increased of effective diffusivity from 3 x 10^{-10} to 5.7 x 10^{-10} m^2/s. In Figure 5diii the coal sample weight of 1.0 g was dried in an elevated temperature from 100 to 250^{o}C using a fixed bed drying. From 100^{o}C to 150^{o}C shows a steeper gradient from Figure 5 with increased of effective diffusivity value from 1.35 x 10^{-10} to 3.55 x 10^{-10} m^2/s, an increase of 163%. In contrast, from 150^{o}C to 250^{o}C shows a less steep gradient in Figure 5 with increased of effective diffusivity value from 3.55 x 10^{-10} to 4.14 x 10^{-10} m^2/s increased of 17% only. This slight increase of effective diffusivity value after 150^{o}C is because at 100^{o}C to 150^{o}C, most of the inherent moisture had diffused out of the coal, resulting in less inherent moisture in the coal. Less inherent moisture in coal leads to drying sample approaching equilibrium moisture content, hence lower % increased of effective diffusivity value.

Besides, it was found out that the superheated steam fluidised bed gave the highest effective diffusivity value followed by nitrogen fluidised bed then fixed bed drying. The reason is due to:

- A fixed bed drying has poorer moisture distribution than a fluidised bed drying.
- Heat and mass transfer rate of a fixed bed drying are different compared to a fluidised bed drying.
- A different hot air medium was used.
- A different sample coal weight was used.

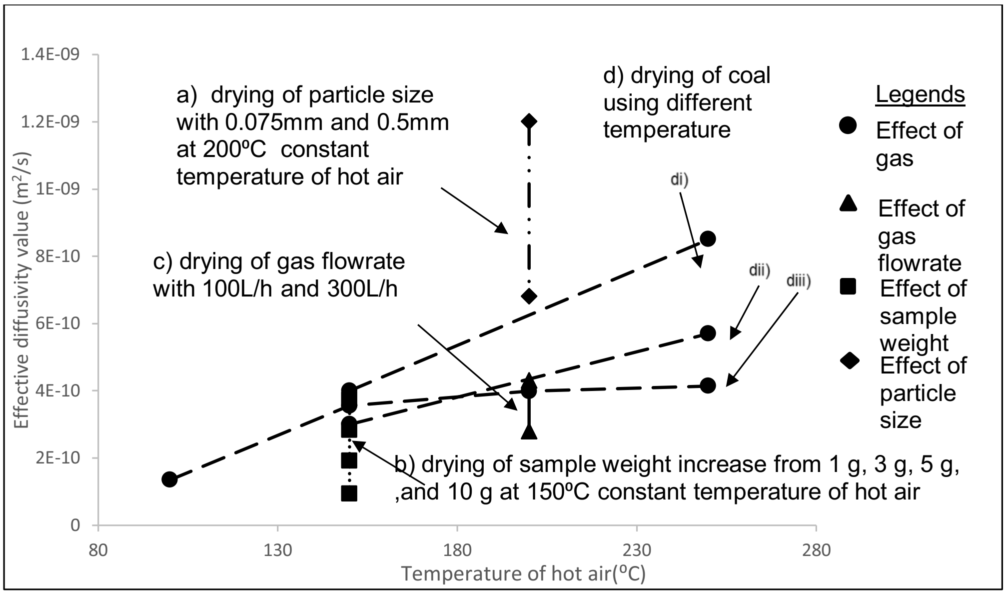

Figure 5. A plot of temperature of hot air versus effective diffusivity using fluidised bed drying. (a) drying of particle size (b) drying of sample weight (c) drying of gas flowrate (d) drying of coal using different temperature

4.3 Microwave drying. Two different parameters were used to evaluate effective diffusivity value in the effect of particle size and microwave power. Power to weight ratio was used as the x-axis in Figure 6 to give a fair comparison between each result by dividing power with sample coal weight. 5 different experiment as shown in Figure 6a, b, c, d, and e with different sample were used to dry using microwave drying method.

In Figure 6a Ximeng lignite was conducted with different particle size of 154 to 600 µm and 1000-1700 µm [12]. Figure 6 shows a vertical line with a constant power to weight ratio of 100 W/g. The result shows a tremendous 93746% increase of effective diffusivity value from 8.45 x10^{-10} m^2/s to 7.93 x10^{-10} m^2/s. This concludes that an increased in coal particle size leads to an increase in effective diffusivity value. The result was completely different from fluidised bed drying method where an increase in sample size will decrease the effective diffusivity. This is because power absorption per unit surface area of sample coal increases when there is an increase in sample size [1]. Microwave drying causes increase the electromagnetic waves which then increases the dielectric loss of water molecule in the coal [18]. This increased in dielectric loss increases the electromagnetic energy absorbed by the coal, hence induces molecular friction in the inherent moisture causing internal heating of the coal. This leads to a faster diffusion from the inside to the surface of the coal through pressure-driven jet flow that enhances moisture loss during microwave drying [1].

Indonesian coal conducted by Fu et al. [19] shows as Figure 6b and c have the same microwave power of 231 W, 385 W , 539 W ,and 700 W. By comparing Figure 6b and c the coal sample size used were 20 mm and 10 mm respectively and coal sample weight are 5.3 g and 2.3 g respectively. Both experiments show an increase of effective diffusivity of 203% from 231 W to 700 W microwave powers. This is because an increased in microwave power leads to an increase electromagnetic energy which give rise to an increase in dielectric loss, and then more electromagnetic energy was absorbed by the sample [19]. The electromagnetic energy absorbed changed into thermal energy which leads to the inherent moisture of the sample to heat up causing inherent moisture to diffuse out to the surface of the coal.

Fu et al. [19] shows the importance of the effect of coal particle size in Figure 6b (size 20 mm) and Figure 6c (size 10 mm). Figure 6b shows an increase of effective diffusivity values from 2.58 x 10^{-8} m^2/s to 5.92 x 10^{-8} m^2/s when the microwave power increased from 231 to 700 W. Figure 6c shows an increase of effective diffusivity values from 6.72 x 10^{-9} m^2/s to 1.71 x 10^{-8} m^2/s when same condition applied. Hence, when coal particle size increased, the effective diffusivity value increased. However, this trend was found to be completely different from the conventional hot air drying and fluidised bed drying where the coal particle size increased, the effective diffusivity value decreased. According to Tahmasebi et al. [1] microwave drying, a sample with larger particle size have higher effective diffusivity value because power absorption per unit surface area for microwave heating increases with increasing surface area (particle size).

Both Ximeng lignite shown as Figure 6d and Indonesian coal shown as Figure 6e shows an increase in power to weight ratio led to increase in effective diffusivity value. Figure 6d was conducted with 5 g, 154 – 600 µm and heated using the microwave power of 500 W and 700 W shows an increase of power to weight ratio from 100 to 140 W/g. The increase in power to weight ratio leads to a 79% increase in effective diffusivity from 3.80 x 10^{-9} m^2/s to 6.80 x 10^{-9} m^2/s. Besides, the increase of power to weight ratio from 8 to 24 W/g significantly increase the effective diffusivity value by 398% for Figure 6e from 8.5 x 10^{-9} m^2/s to 4.23 x 10^{-9} m^2/s by conducting Indonesian coal with 50 g sample size. Hence, higher power to weight ratio means that a higher microwave energy absorption for each gram of coal sample. In conclusion, a higher power to weight ratio results in a higher effective diffusivity value.

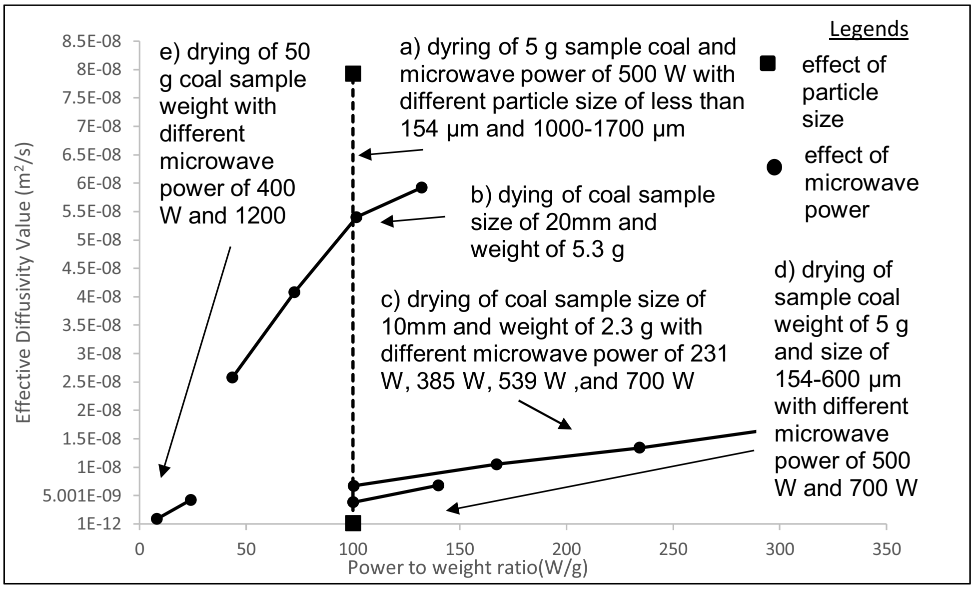

Figure 6. Power to weight ratio versus effective diffusivity value. (a) drying with different particle size (b) drying with different microwave power (c) drying with different microwave power (d) drying with different microwave power (e) drying with different microwave power

5. Conclusions

This article presents a critical review in drying of low rank coals. Microwave drying and fluidised bed drying was found to be the more efficient method to dry low rank coal than conventional hot air drying. The microwave drying heats up the internal part of the coal, thus the cavitations of liquid inside the particle size increase led to a higher drying rate and effective diffusivity value whereas fluidised bed causes uniform distribution of heating medium to heat up low rank coal. The fluidisation result was reported better in term of mixing performance and high heat and mass transfer compared to the conventional hot air drying. It was found that few parameters that could significantly affect the effective diffusivity of low rank coal in conventional hot air drying are increasing temperature and flow rate of hot air led to an increase in effective diffusivity value. For fluidised bed drying, increasing the particle size and weight results in a decrease in effective diffusivity value. Further to this, an increase in heating medium flow rate and temperature led to an increase in effective diffusivity value. Finally, increased of microwave power and particle size increased the effective diffusivity values. For the mathematical model, Midilli-Kucuk model was by far the best and most commonly used thin layer drying model for drying of low rank coal. In fluidised bed drying, the Midilli-Kucuk was the best fitted model to model the drying kinetics of low rank coal whereas the Wang&Singh model was the best drying model to model a fixed-bed drying kinetics. Microwave drying kinetics can be modelled either using the Page Model or the Midilli-Kucuk model.

- Hybrid drying methods such as microwave assisted fluidised bed drying method can be further investigate to improve the drying technologies in low rank coal.
- More empirical models can be discussed for drying coarse particle size of low rank coal instead of thin layer particle.

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